• 12/08, Trigger, front-end-electronics and data acquisition system.
• 12/15, Data-analysis technique and tools.
• 12/22, Statistics for data analysis and physics interpretation.
Trigger and Electronics in HEP experiments

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Outline of Trigger and Electronics

- Event rate and luminosity.
- DAQ: Data Acquisition System.
- Trigger: what, why and how?
- Electronics: ADC, TDC, Logical modules.
# Accelerators

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Time between collisions (ns)</th>
<th>Luminosity $(10^{30} \text{ cm}^{-2}\text{s}^{-1})$</th>
<th>Energy (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CESR (CLEO)</td>
<td>4.2</td>
<td>2000</td>
<td>6</td>
</tr>
<tr>
<td>KEKB (Belle)</td>
<td>2</td>
<td>10,000</td>
<td>8 x 3.5</td>
</tr>
<tr>
<td>PEP-II (BaBar)</td>
<td>4.2</td>
<td>3,000</td>
<td>9 x 3.1</td>
</tr>
<tr>
<td>LEP (Aleph, Delphi, Opal, L3)</td>
<td>2200</td>
<td>50</td>
<td>101 (103??)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Time between collisions (ns)</th>
<th>Luminosity $(10^{30} \text{ cm}^{-2}\text{s}^{-1})$</th>
<th>Energy (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA (H1, Zeus)</td>
<td>96</td>
<td>14</td>
<td>920 x 30</td>
</tr>
<tr>
<td>TeV (DØ, CDF)</td>
<td>396 (132)</td>
<td>200</td>
<td>2,000</td>
</tr>
<tr>
<td>LHC (Atlas, CMS)</td>
<td>25</td>
<td>10,000</td>
<td>14,000</td>
</tr>
</tbody>
</table>

Source: PDB’98
How to define a beam?
Structure of Beam Spill

5-Feb-97
14:53:55

A: M1
.2 ms
10.0 mV

B: A
1 μs
4.00 mV

C: B
.1 μs
3.00 mV

D: C
5 ns
4.00 mV

Main Trace
200 μs/div

Zoom of A
1 μs/div

Zoom of B
100 ns/div

Zoom of C
5 ns/div

Beam
Event Rate & Luminosity

Event Rate = \( \frac{N_{\text{events}}}{s} = \sigma \frac{N_{\text{flux}}}{F} = \sigma \ast \text{Luminosity} \)

\[ F = \frac{A}{N_A \ast \rho \ast \text{len}} \]

s : time duration
F : target constant
\( \sigma \) : interaction cross section of beam with target
A : Atomic weight
\( N_A \) : Avogadro constant
\( \rho \) : Density
len : target length
The total photo-production cross section $\gamma p$ for energy above 4 GeV is about 120$\mu$b (1 barn = $10^{-24}$cm$^2$=100fm$^2$).

Photon flux is about $10^6$ Hz.

A liquid hydrogen target of length 11 cm: $F= 2.1$ b.

Luminosity $= 10^6 / 2.1 = 0.48$ $\mu$b$^{-1}$ s$^{-1}$

Event rate $= 120 * 0.48 = 58$ s$^{-1}$
LHC Example

LHC design
~1 GHz input rate
~1 kHz W events
~10 Hz top events
<<< 1 Hz Higgs events

DAQ speed ~ 100 Hz

Level-1 Triggers
1 GHz → 100 kHz
High Level Triggers
100 kHz → 100 Hz
Definition and Need of Trigger

• A trigger is an electronic signal indicating the occurrence of a desired temporal and spatial correlation in the detector signals: $B(\text{beam}) \otimes F(\text{final state in detector})$

• Goal:
  – Select rare events and suppress background events.
  – Reduce ‘dead time’ of data acquisition system by reducing the amount of data taking.
  – Reduce the cost of data storage and effort the data reduction.
Dead Time

- Definition: the non-sensitive period of the detector or the electronics.
- The loss of triggers caused by dead time must be corrected for and kept small for reasons of efficiency.
- Dead time for detectors: nsec for scintillators and up to micro- and milliseconds for wire chambers.
- Dead time for electronics: nsec for NIM modules and micro-sec for DSP.
- Dead time for DAQ: order of msec.
- The trigger needs finite time for its decision.
- Trigger cannot cause deadtime during decision
- To make deadtime timeless must have pipeline to store everything in FE
  - Switched Capacitor Arrays (SCAs)
  - DRAM
  - Shift Registers
  - Sample & Hold Shaping
  - Old fashion Delay Lines

<table>
<thead>
<tr>
<th>Trigger Output</th>
<th>Data for BX #</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>5</td>
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<tr>
<td></td>
<td>6</td>
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<td></td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Dec. for BX 1</td>
<td>10</td>
</tr>
<tr>
<td>Dec. for BX 2</td>
<td>11</td>
</tr>
<tr>
<td>Dec. for BX 3</td>
<td>12</td>
</tr>
<tr>
<td>Dec. for BX 4</td>
<td>13</td>
</tr>
<tr>
<td>Dec. for BX 5</td>
<td>14</td>
</tr>
<tr>
<td>Dec. for BX 6</td>
<td>15</td>
</tr>
<tr>
<td>Dec. for BX 7</td>
<td>16</td>
</tr>
</tbody>
</table>
• Bubble Chambers, Cloud Chambers, etc. \((4\pi)\)
  - DAQ was a \textit{stereo photograph}!
  - Low level trigger was the accelerator cycle
    • Each expansion was photographed
  - High level trigger was \textit{human} (scanners).
  - No Trigger
Typical Designs

• Required rejection is orders of magnitude
• Cannot do it at beam crossing rate
  - Algorithms to attain required rejection are too sophisticated.
  - Accelerator backgrounds can also contribute to the problem
    • $e^+e^-$ vs pp
• Multi-Level trigger
  - Algorithms implemented in Hardware
    • Specialized, often matched to geometry of detector
  - Algorithms implemented in Software
    • Farm

Detector

Course Grained Readout

Level 1
(HW)

DØ: 7MHz

Full Resolution Readout

Level 2+
(SW/HW)

DØ: 10kHz

Real Time

DØ: 50Hz

To Storage
Data Flow

Data Link to Readout Buffers
  Optical Technology

Level-1 Triggers
  High Density FPGA, Custom ASIC (?)

Data Processing and Transfer
  Custom Electronics, Bus Speed

Level-2 Hardware Triggers
  Trigger Primitive Processors

Event Building Switch
  Gigabit Ethernet++, ATM

Level-3 Processor Farms
  Operating System, Number of Nodes, Software

Data Archiving
  Tape Cost, Storage Technology, Ability to Analyze
Classification of Higher-Level Triggers

- Track multiplicity of the event
- Direction of particles
- Deflection or curvature of particles to measure momentum
- Co-planarity of the event
- Type of particle
- Deposited energy
- Missing energy
- Invariant mass
- Interaction point of event or secondary interaction
Trigger of Invariant Mass

Fig. 1.47. Spectrometer to study $\mu^+\mu^-$ pairs. The target is surrounded by an absorber. Wire chambers in front of and behind the magnet define the trajectories.

Fig. 1.48. Processor to find invariant mass. The processor computes first the
Multi Level Trigger

• Level 1 is hardware based
  – Identifies Jets, Tracks, Muons, Electrons
  – Operates on reduced or course detector data

• Level 2 is often a composite
  – **Hardware** to preprocess data
    • Some Muon processors, Silicon Triggers
  – **Software** to combine
    • Matches, Jet finders, etc.

• Level 3 is a PC farm
  – General Purpose CPUs
Electronic Modules
Level 1 Trigger

- NIM (nuclear instrumental module) standard, operating at a speed of < 10 ns.
- Discriminator
- Coincidence register
- Logical unit: AND/OR
- Interrupt (gate) generator
- Fan-in/Fan-out: linear and logic
- Gate generator

http://www.lecroy.com/lrs/dsheets/dslib.htm
Discriminator and Coincidence

**Discriminator**

![Discriminator Diagram](image)

*Fig. 14.14.* Discriminator operation: only signals whose amplitude is greater than the fixed threshold trigger an output signal.

**Coincidence**

![Coincidence Diagram](image)

*Fig. 15.8.* A system for coincidence measurement.

*Fig. 15.9.* Coincidence between pulses.
Trigger for Rutherford Scattering

Fig. 16.6. Simple set-up for Rutherford scattering
Trigger for 2-body Scattering

Fig. 16.7. A simple set-up for 2-body scattering

\[ S_1 S_2 A B \bar{C} \]
Fig. 16.8. Detector set-up for measuring muon lifetime

\[ \mu \rightarrow e + \nu + \bar{\nu} \]
Trigger for Muon Lifetime Measurement

Fig. 16.9. Electronic logic for muon lifetime measurement
Global Structure of BELLE DAQ System
Front-End-Electronics in Data Acquisition

• Electronic module:
  – ADC: analog-digital converter
  – TDC: time-digital converter
  – Latch
  – Memory
  – Interrupt generator

• Bus system:
  – CAMAC
  – FASTBUS
  – VME
  – PCI

http://www.lecroy.com/lrs/dsheets/dslib.htm
• Uses time-to-charge converters to supply Charge Multiplexers with charge proportional to the time between Common Start and Stops.

• Measure the charge by high-resolution (12-bit) ADC.
• the input to the ADC is sampled and the result is stored as charge on a capacitor. After a short interval, the capacitor is discharged at a constant rate, producing a time proportional to the input charge. The time is measured by counting the number of oscillator pulses during the discharge interval.
Lecroy 2249A CHARGE ANALOG-TO-DIGITAL CONVERTER

- Charge or Voltage Input
- High Sensitivity, -0.25 pC or -1 mV
- Wide Dynamic Range, 10 or 11 Bits
- Excellent Linearity
- Fast Conversion, 100 µsec
- Fast Clear Input
Lecroy 1875A HIGH RESOLUTION TIME-TO-DIGITAL CONVERTER

- High Sensitivity, to 25 psec/Count
- Short Conversion Time, 10 µsec + 2.5 µsec Per Hit Channel
- Fast Clear, 950 nsec
- Multiple Event Buffer, 8 Events
- Common Start Mode of Operation
CAMAC Crate
VME 6U & 9U
Backplane of VME
FASTBUS
## Characteristics of Data Bus

<table>
<thead>
<tr>
<th>Item</th>
<th>CAMAC</th>
<th>FASTBUS</th>
<th>VME</th>
<th>PCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth [Mbytes/s]</td>
<td>3</td>
<td>40</td>
<td>160</td>
<td>264</td>
</tr>
<tr>
<td>Address width</td>
<td>7/25/4</td>
<td>32</td>
<td>64</td>
<td>32/64</td>
</tr>
<tr>
<td>Data width</td>
<td>24</td>
<td>32</td>
<td>8/16/32/64</td>
<td>32/64</td>
</tr>
<tr>
<td>A/D multiplexed</td>
<td>no</td>
<td>yes</td>
<td>yes/no</td>
<td>yes</td>
</tr>
<tr>
<td>Board size [mm²]</td>
<td>183 × 305</td>
<td>366 × 403</td>
<td>233 × 160, 366 × 403</td>
<td>311 × 107</td>
</tr>
<tr>
<td>Number of connectors</td>
<td>1</td>
<td>1</td>
<td>1/2/3</td>
<td>1</td>
</tr>
<tr>
<td>Type of connector</td>
<td>82 pin direct</td>
<td>132 pin distributed</td>
<td>96/120 pin central</td>
<td>Microchannel central</td>
</tr>
<tr>
<td>Arbitration</td>
<td>central</td>
<td>distributed</td>
<td>central</td>
<td>4 levels</td>
</tr>
<tr>
<td>Interrupt</td>
<td>LAM pattern</td>
<td>message passing</td>
<td>7 levels</td>
<td>synchr</td>
</tr>
<tr>
<td>Bus protocol</td>
<td>synchr/asynchr</td>
<td>asynchr</td>
<td>asynchr</td>
<td>no</td>
</tr>
<tr>
<td>Serial bus</td>
<td>extra system</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Geographical addressing</td>
<td>yes</td>
<td>yes</td>
<td>yes/no</td>
<td>yes</td>
</tr>
<tr>
<td>Chip set available</td>
<td>no</td>
<td>private</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>
SPring-8 Flash ADC

VME 9U, 32 channel, 40 MHz, 10 bits.
How much Data we get?

- 40 MHz sampling rate = 25 nsec
- Strobe width = 10 micro-sec = 10,000 nsec
- 10 bits
- 100 channels
- Total for one event = 10000/25*10*100 = 400 Kb = 50 KB
- 50 Hz DAQ rate => 2.5 MB per sec =>150 MB per min =>9 GB per hour
Field Programmable Gate Array

- Board on a chip
  - Revolutionized the way board design is done.
  - Logic design is not frozen when the board is laid out.
    - But much faster than running a program in microcode or a microprocessor.
  - Can add features at a later time by adding new logic equations.
  - Basically a chip of unwired logical gates (flip-flops, counters, registers, etc.).
This design has the advantages as follows:
(1) Zero Dead time.
(2) Flexible algorithm can be installed into the DSP.
(3) User can select the functions.
(4) Divide each block into individual module without conflicting.
The Control Flow of FADC

For each channel

- Trigger Count \(*_{\text{Veto}}\)
- CPLD FADC Trigger Clock 100MHz
- Trigger signal

Preamplifier Module

FADC Module

Master VME CPU

Slave

DAQ Start

- Trigger, Conversion

< 5 events

- No
  - Send IRQ to VME CPU
  - DAQ READ FIFO
  - DAQ send Reset
  - FADC clear BUSY
  - Clear trigger Veto

- Yes

Reset
Cosmic ray experiment

- PMT 1
- Scintillation
- Discriminator
- Coincidence
- Gate Generator
- 9U crate with VME bus
- Sun Solaris CPU
- Fadc ADC Module
- Ethernet Storage HD
- CH 1
- CH 2
- Busy
- Trigger
Energy loss of Particles

Cosmic ray

PMT 1

Plastic Scintillator

PMT 2

Landau distribution
The ATLAS TDAQ Project:
Trigger, DAQ and DCS

Introduction

The TDAQ project’s task is to design, implement and later run the ATLAS trigger and data acquisition system. The project is divided into three sub-projects or systems: The Level-1 Trigger (LVL1), the High-Level Trigger (HLT) and the Data Acquisition (DAQ), each of which is again divided into various sub-systems. In addition, the Detector Control System (DCS) is a part of the DAQ, but also one of the ATLAS Technical Coordination.

Management

The TDAQ project is run by the TDAQ management team and is represented by a TDAQ project leader (PL. currently L. Mapelli). Each of the three sub-projects or systems is run by the respective project leader (N. Ellis for LVL1, C. Bee for HLT and L. Mapelli for DAQ). Each system is divided into several sub-systems, managed by a coordinator. At each level, the organisation is completed by a number of cross-system activities.

Important bodies for the TDAQ project are
- the TDAQ Steering Group (SG) and
- the TDAQ Institute Board (IB).

The representatives of the TDAQ community on other bodies are listed here.

Test Beam and Testbed Activities

The DAQ group provides support for ATLAS test beam activities throughout the data-taking period. On-call shifts have been organized around the clock in order to ensure a prompt response in case of problems.

• Data Analysis Techniques for High-Energy Physics, R. Fruhwirth et al., Cambridge University Press 2000.
• Introduction to Experimental Particle Physics, R. C. Fernow, Cambridge University Press 1986.
• Data Acquisition and Trigger Upgrades, Jamie Nagle, RHIC Detector Workshop 2001.
• Triggering In High Energy Physics, Gordon Watts, Instr’ 99.